PRECISION MEASUREMENT OF THE HIGGS BOSON MASS AND SEARCH FOR DILEPTON MASS RESONANCES IN $H \to 4\ell$ DECAYS USING THE CMS DETECTOR AT THE LHC

By

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A DISSERTATION PRESENTED TO THE GRADUATE SCHOOL
OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT
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Major: Physics

The mass of the Higgs boson is measured in the $\mathrm{H} \rightarrow \mathrm{ZZ}^* \rightarrow 4\ell$ ($\ell = \mathrm{e}, \mu$) decay channel and is found to be TODO:MASS—the world's best measurement to date. The data for the measurement were produced from proton-proton (pp) collisions at the Large Hadron Collider with a center-of-mass energy of 13 TeV during Run 2 (2016–2018), corresponding to an integrated luminosity of 137.1 fb^{-1}, and were collected by the Compact Muon Solenoid experiment. This measurement uses an improved analysis technique in which the final state muon tracks are constrainted to originate from the primary pp vertex. Using data sets from the same run, a search for low-mass dilepton resonances in Higgs boson decays to the 4ℓ final state is also conducted. No significant deviation from the standard model prediction is observed.

CHAPTER 1
INTRODUCTION

NEW [1].

The Universe, while overwhelmingly vast, is comprised of a curiously small number of indivisible particles. As shown in Fig. 1-1, these *elementary* particles can be split into two main kinds: a mere 12 *matter* particles (green and pink) that comprise all detectable matter and 4 *force* particles (red) that convey forces between the matter particles. Although it is fascinating to wonder how can so much diversity can arise from just 16 "simple" building blocks, it is the mission of particle physicists to understand the underlying mathematical structure that describes Nature in as simple—and accurate—a theory as possible. The best theory developed so far is called the Standard Model (SM) of particle physics (see Chapter **??** for a mathematical overview).

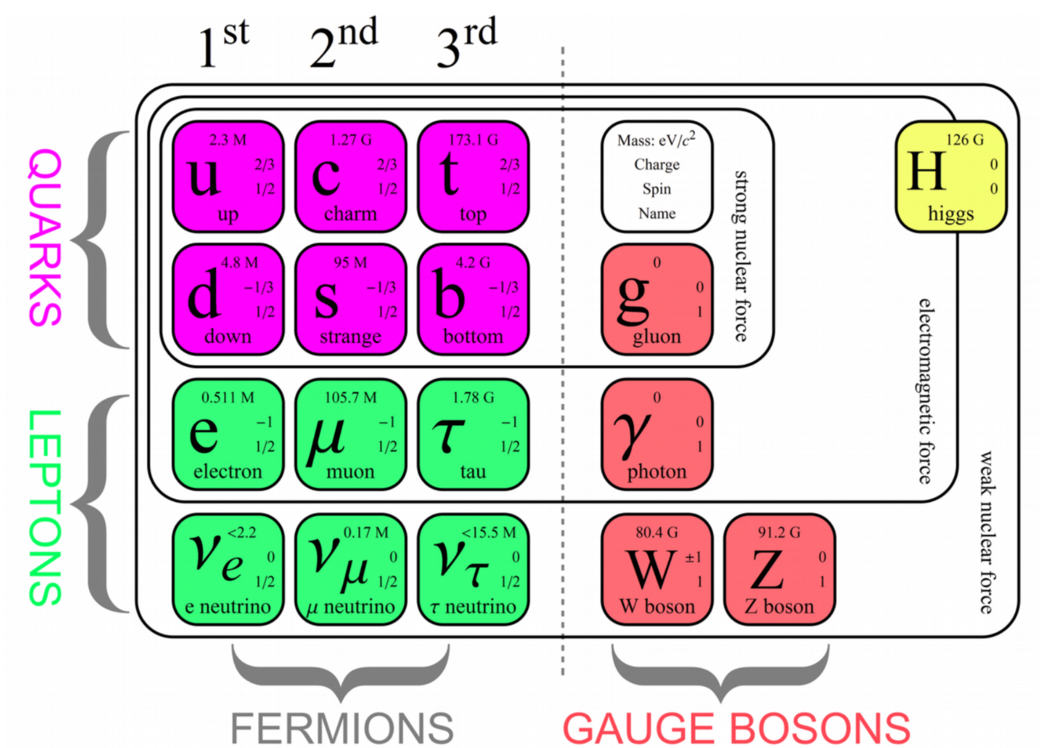

Figure 1-1. TODO

The SM has bore witness to many triumphs over its approximately 70-year development: it predicted the existence of quarks which were experimentally confirmed in the mid-1970s; it predicted the existence of the tau neutrino which was experimentally confirmed in 2000; its most groundbreaking prediction was experimentally confirmed on July 4, 2012—almost exactly 10 years ago from the date of this dissertation writing—when the ATLAS and CMS collaborations announced the discovery of the Higgs boson [2].

The Higgs boson (H) is a critical piece of the SM because, without it, it is the quantum excitation of the so-called Higgs field, an all-pervasive field throughout spacetime Before

It is necessary to scrutinize the properties of this new particle to check whether it truly is the H predicted by the SM—or perhaps something else entirely. Thus, the Large Hadron Collider accelerates protons to near-light speeds

A major shortcoming of the SM is its inability to predict the masses of these particles.

The SM was not able to predict the masses of these particles until 1964 when the Brout-Englert-Higgs mechanism suggested that It wasn't until 1964 that the Brout-Englert-Higgs mechanism gave a self-consistent way to : by breaking the electroweak gauge symmetry of the vacuum would give rise to non-zero masses of the weak gauge bosons. This would yield a secondary effect too: there should exist a fundamental scalar boson which is the quantum of the so-called "Higgs field". On July 4th, 2012, this Higgs boson was discovered.

This dissertation presents the world's most precise measurement of the Higgs boson mass (m_{H}) to date, using proton-proton collision data from the LHC Run 2, collected and analyzed by the CMS Experiment. The value of m_{H} has been measured previously TODO:CITE LOTS OF PEEPS [3] but it is important to always strive for lower uncertainties (i.e. to increase the precision) on the mass value, since the very stability of our universe theoretically depends on m_{H}, as shown in Fig. 1-2. Furthermore, the value of m_{H} sets limits on the masses of most of the other elementary particles.

The measurement of m_{H} presented in this dissertation utilizes the following improvements compared to previous measurements:

- Utilizing nearly four times as much collected data from Run 2 $\left(\mathcal{L}_{\mathrm{int}} = 137.1\,\mathrm{fb}^{-1}\right)$ vs. the data used for the 2016 measurement $\left(\mathcal{L}_{\mathrm{int}} = 35.9\,\mathrm{fb}^{-1}\right)$.
- Four final-state categories are used: 4μ, 4e, 2e2μ, 2μ2e. In previous measurements, the last two final states (the mixed-flavor states) were combined, when truly they have different kinematical properties (depending on into which lepton pair the Z_1 decayed): different peak

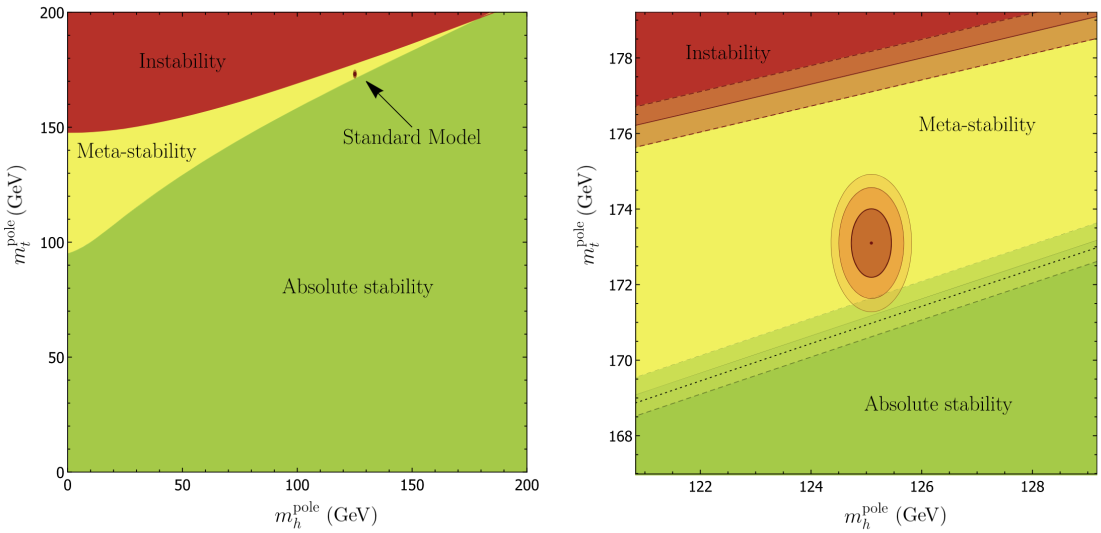

Figure 1-2. (Left) Theoretical stability regions of our universe based on the pole masses of the top quark $\left(m_t^{\text{pole}}\right)$ and Higgs boson $\left(m_h^{\text{pole}}\right)$. (Right) A closeup of the SM region of the left plot. The contours represent the 68%, 95%, and 99% confidence levels based on the experimental uncertainties of m_t^{pole} and m_h^{pole}. Plots taken from [4] and units added to all axes.

widths (instrumental resolutions), different signal efficiencies, and different relative levels of reducible background.

- Ultra-Legacy (UL) reconstruction is used for muon, electron, photon, and jet tracks. This signficantly improves electron momenta and improves the other particle momenta, though to a lesser degree.

- The measurements of muon p_{T} are improved by constraining the muon tracks to originate from the interaction vertex (also called a *vertex constraint*).

- When extracting the value of m_{H} in past measurements, a 3D pdf $\left(m_{4\ell}, \sigma_{m_{4\ell}}, \mathcal{D}_{\text{bkg}}^{\text{kin}}\right)$ was built into a factorized form $f\left(m_{4\ell}, \sigma_{m_{4\ell}} \,\middle|\, m_{\text{H}}\right) \cdot g\left(\mathcal{D}_{\text{bkg}}^{\text{kin}} \,\middle|\, m_{4\ell}\right)$, which was later found to contain an existing correlation between $\sigma_{m_{4\ell}}$ and $\mathcal{D}_{\text{bkg}}^{\text{kin}}$. To account for this correlation, now the events are split into 9 categories based on the per-event *relative* mass uncertainty $\left(\frac{\sigma_{m_{4\ell}}}{m_{4\ell}}\right)$ and, for each, a 2D pdf $\left(m_{4\ell}, \mathcal{D}_{\text{bkg}}^{\text{kin}} \,\middle|\, m_{\text{H}}\right)$ is built.

- The systematic uncertainties on electron and muon momentum scales $\left(p_{\text{T}}^{\text{e},\mu}\right)$ are reduced, thanks to a more detailed analysis on the uncertainties. This has the additional effect of significantly reducing the uncertainty on the per-event four-lepton mass resolution.

This dissertation is organized into the following chapters: Chapter 1 (*this chapter*) discusses the importance and motivation for measuring the mass of the Higgs boson; Chapter **??** introduces the standard model (SM) of particle physics and its mathematical framework, including the Brout-Englert-Higgs (BEH) mechanism; Chapter **??**; Chapter **??**; Chapter **??**; Chapter **??**; Finally, Chapter **??**.

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